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Global assessment of ecological risks associated with farmed fish escapes

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ABSTRACT

Aquaculture is the world's fastest growing food-producing sector and currently the main source of fish supply. However, environmental sustainability is one of the main challenges faced by the industry, in particular the inevitable occurrence of fish escapes, which are considered a major threat to marine ecosystems. Here we evaluated the risks associated with the impacts of introducing non-native species, the genetic introgression of farmed fish into wild stocks and the spread of pathogens and parasites through escapes of farmed fish at a global scale. Our analysis indicated that a nearly a third of marine ecoregions of the world are to some extent at risk from the impacts of fish escapes. We estimated that 26.5% of global production comprises non-native species, equating 1.74 million tonnes per year, with the Magellanic province in Southern Chile being a hotspot for ecological invasion impacts, owing to a large production of non-native salmonids. Genetic risk hotspots were also identified in East China and Yellow Sea, which support the world's largest and more diverse production of native fish. The combination of high pathogen diversity and production levels recorded for East China and the Mediterranean Sea resulted in the highest pathogenic risk predicted for these provinces. When considering the combined risk of these three stressors the warm temperate Northwest Pacific ranked highest in terms of overall risks. We highlight the need of preventive and mitigation measures to reduce fish escapes, particularly in sensitive ecoregions, considering risk assessment for farming non-native species and the critical role of policy makers in implementing these measures to allow the sustainable development of aquaculture.

1. Introduction

Aquaculture is the world's fastest expanding food production sector, with an annual growth rate of 37% recorded in 2016 and a projected production of 109 million tonnes by 2030 (FAO, 2018). As the global supply of fish from wild fisheries is limited, finfish aquaculture has the opportunity to meet the growing demand through increased production. However, the future development of the industry must be based on the sustainable use of natural resources, in order to minimise potential impacts on the marine environment (Soto et al., 2008).

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A range of local ecological impacts are associated with marine finfish aquaculture, including negative effects on the seabed (Pearson and Black, 2000) and the water column (Sarà, 2007). Finfish are mostly intensively produced in natural water bodies using floating cages or "net-pens". Because of the open nature of net-pen systems, there is an inherent high risk of fish escapes into natural habitats, which is regarded as a major problem for the industry (Soto et al., 2001; Naylor et al., 2005; Jensen et al., 2010; Sepúlveda et al., 2013). Fish escapes are an inevitable occurrence caused by several internal and external factors, which result in the occasional release of a large number of individuals (massive escape events) or the recurrent release of a small number of fish (chronic or leakage escapes, Naylor et al., 2005). The main internal cause of fish escapes are technical and operational failures of farming equipment, primarily through structural failure of containment equipment (e.g. nets). Net failure can occur in many ways, including biting by caged fish (Sanchez-Jerez et al., 2008), abrasion, holes caused by wear and tear of the netting, and operational accidents (Jensen et al., 2010; Arechavala-Lopez et al., 2018). External causes of escapes are commonly linked to oceanic conditions (e.g. storms, Toledo-Guedes et al., 2014a), predators biting, sabotage or maritime accidents. Substantial fish escapes have been recorded in most key finfish producing regions (Soto et al., 2001; Naylor et al., 2005). For example, over one million salmon were reported to have escaped from Scottish farms during the period from 2002 to 2006 (Thorstad et al., 2008). In the Mediterranean ca. 9 million farmed fish were reported to have escaped over a three-year period (Jackson et al., 2015). In Southern Chile a heavy storm recently cause the escape of ca. 650,000 salmon from a single net-pen farm (Gomez-Uchida et al., 2018). In any cases, the probability of fish escapes at a regional scale increases with fish production intensity, either as a result of increases in farm fish density or in the number of farms (Jensen et al., 2010; Sepúlveda et al., 2013).

Escapes not only represent a considerable economic loss for the farmers, but can have drastic ecological, genetic, pathogenic and socio-economic impacts. The potential negative effects vary in relation to the intensity and frequency of occurrence, the location in relation to wild populations, whether the species are native or non-native, and the vulnerability of the recipient environment (Jensen et al., 2010). In this sense, marine ecosystems are much more susceptible to large-scale aquaculture-mediated invasion pressure than previously thought. Finfish aquaculture can also have a "farming up" effect, as escapes of high trophic level species increase the average trophic level of natural fish communities (Toledo-Guedes et al., 2014b).

Escapes are particularly problematic in areas outside the species' native ranges or where local wild populations are rare, representing an important vector of introduction and subsequent spread of non-native species (Crawford and Muir, 2008). More frequent and extensive escape events translate in higher propagule pressure, which is an important determinant of the success of biological invasions (Simberloff, 2009). Ecological impacts of non-native species include direct competition for resources with wild fish (Soto et al., 2001; Valero-Rodriguez et al., 2015), predation (Arismendi et al., 2009), alterations to habitat complexity (Sala et al., 2011), which can result in declines in native fish populations (Crowl et al., 1992). When escapees are native species, there is the risk of genetic introgression of farmed fish into wild populations (Bolstad et al., 2017). Most farmed fish have low genetic diversity as a result of selective breeding for favourable production traits over several generations. Thus, genetic introgression of farmed fish can result in alterations in the genetic composition, long-term loss of fitness, adaptability and reduced survival of wild fish populations (Glover et al., 2010; Miralles et al., 2016).

In addition, to the ecological and genetic risks, net-pen aquaculture can increase the risk of transmission of diseases and parasites into wild fish (Arechavala-Lopez et al., 2013). The proliferation and spread of pathogens in marine farms is an increasing problem, exacerbated by the expansion, diversification and intensification of the industry (Costello, 2006, 2009; Murray, 2009). Crowded net-pen environments promote favourable conditions for disease development and subsequent spread, given their direct contact with natural habitats (Diamant et al., 2007). Even though diseases are transmitted through interactions between the host, the pathogen and the environment, infected escapees or wild fish moving within the plume of infected farms represent important vectors for transmission (Olivier, 2002). The risk of pathogen exchange is also increased by the aggregation of wild fish around net-pen farms due to feed availability and shelter (Dempster et al., 2009). There is mounting evidence for these types of interactions, which are a major concern for the sustainability of wild fisheries.

While the extent, causes and the ecological consequences of fish escapes have been well documented for individual species and ecoregions (e.g. salmonids in their main farming regions), there is a lack of knowledge about the global extent of this issue. Furthermore, there is uncertainty about the combined risks associated with net-pen aquaculture of multiple species farmed simultaneously in given ecoregions. Many of the legislative measures regarding to fish escapes are defined at a local or regional level (i.e. at a small scale) and do not consider the environmental issues associated with global species translocation. This is a crucial aspect for the development of precautionary and risk-based management measures aiming to improve the sustainability of global aquaculture practices.

The objective of this study was to conduct a global assessment of the ecological, genetic and pathogenic impacts risk associated with escapes of farmed fish into natural marine ecosystems. We used an exhaustive systematic search of global datasets and literature to collate information on fish production, pathogenic agents, species distribution ranges and ecological traits for the thirty most extensively farmed fish species globally. This information was combined to provide a visualisation of global geographical patterns of ecological, genetic and pathogenic impacts risk. Finally, we rank marine provinces of the world based on the cumulative risk associated with fish escapes, with the aim of highlighting key issues for fish escapes management across ecoregions of the world.

2. Methods

Marine fish production data was obtained by country and regions from the FAO statistics database (www.fao.org/fishery/statistics). We considered the thirty most extensively farmed marine fish species in net-pen systems in terms of annual mean biomass production between 2011 and 2016 (Table 1). Only fish reported at the species level were included to allow us to ascertain their native distribution ranges. Annual mean production was calculated for each species and mapped into Marine Ecoregions of the World system (Spalding et al., 2007), which provides a representative and ecological relevant global biogeographic framework, where world coastal areas classified in a nested system of 12 realms, 62 provinces, and 232 ecoregions. Country production data was matched at the ecoregion level (hereafter referred as MEOW) and when fish species were farmed in more than one MEOW per country, we used the Sea Around Us mariculture dataset (Pauly and Zeller, 2015) to allocate production proportionally. Native range distribution for each species was obtained from AquaMaps (Kaschner et al., 2006) and used to determine their introduction status, i.e. introduced or native to their farming MEOW. Introduction status was used to calculate the average annual production of native and non-native species in each MEOW. Given the positive correlation between production levels and escape risk (Jensen et al., 2010), we used production data as a proxy for escape risk. Production was $\log_{10}$ transformed to reduce the influence of MEOWs with extremely high production levels, for all score calculations described below.

We considered three types of risks associated with the impacts of fish escapes, namely invasive, genetic and pathogenic. Invasive risk was only associated with escapes of non-native species. Because higher propagule pressure and diversity of non-native species generally increase invasion risk (Shea and Chesson, 2002), an "invasive risk score" was calculated as the sum of the product between "invasiveness" and the $\log_{10}$ transformed production of each non-native species farmed in a given MEOW. "Invasiveness" was based on the trophic level (TL), maximum observed length (Lmax) and the growth coefficient (K) of each species obtained from FishBase (www.fishbase.org). Large body size (i.e. large Lmax) and fast growth (i.e. large K) represent common invasive traits (Kolar and Lodge, 2001; Vila-Gispert et al., 2005), whereas TL is a proxy for predation pressure. These three ecological parameters were scaled from 0 to 1 and then averaged to define a gradient of "invasiveness" across the thirty study species (Table 1). K is a parameter of the von Bertalanffy growth function that measures the exponential rate at which the asymptotic length is approached. We used the inverse, so large K^{-1} values indicated rapid growth. TL is defined as the position of a species in the food chain and is calculated as a function of the number, relative contribution to the diet and TL of its prey (Froese and Pauly, 2000). It ranges from 1 to 5, with higher values representing higher positions in

Table 1
Summary of ecological traits (Lmax = maximum observed length, TL = trophic level, K = growth coefficient, Inv. = invasiveness, Pat = number of pathogens), number of producing Marine Ecoregions of the World (MEOW) and production levels by status of introduction (N = native and NI = non-native) for the thirty most extensively farmed marine fish species in net-pen systems globally.

Species	Common name	Lmax	TL	K	Inv.	Pat.	MEOW		Production		Total
							NI	N	NI	N	
Salmo salar	Atlantic salmon	150	4.5	0.23	0.55	49	10	14	496.7	1829.8	2326.5
Oncorhynchus mykiss	Rainbow trout	122	4.08	0.52	0.66	22	15	3	257.1	0.1	257.2
Seriola quinqueradiata	Japanese amberjack	150	3.96	0.33	0.53	28		5		148.3	148.3
Dicentrarchus labrax	European seabass	103	3.47	0.17	0.31	31	5	12	0.6	122.2	122.8
Lateolabrax japonicus	Japanese seabass	102	3.36	0.18	0.3	22		5		117.5	117.5
Sparus aurata	Gilthead seabream	70	3.7	0.28	0.39	50	6	10	2.2	112.4	114.6
Chanos chanos	Milkfish	219.6	2.4	0.19	0.25	19	4	7	52.9	51.2	104.1
Larimichthys crocea	Large yellow croaker	80	3.72	0.23	0.37	10		4		100.2	100.2
Trachinotus blochii	Snubnose pompano	122.1	3.74	0.17	0.37	13	2	5	29.8	59.7	89.5
Oncorhynchus kisutch	Coho salmon	107.95	4.18	0.1	0.38	13	2	1	63.1	11.9	75
Pagrus auratus	Silver seabream	130	3.59	0.1	0.3	34	1	5	2.5	67.5	69.9
Scophthalmus maximus	Turbot	122	4.36	0.25	0.52	14	2	8	56.5	10.2	66.7
Sciaenops ocellatus	Red drum	155	3.74	0.4	0.55	14	8	2	60.9	1.6	62.4
Rachycentron canadum	Cobia	200	3.82	0.31	0.53	18	1	15	0	52.3	52.4
Pseudocaranx dentex	White trevally	122	3.92	0.17	0.39	7		4		49.6	49.6
Paralichthys olivaceus	Bastard halibut	103	3.72	0.15	0.33	27	1	5	0	46.4	46.4
Sebastes schlegelii	Korean rockfish	65	3.76	0.09	0.27	15		3		24.8	24.8
Takifugu rubripes	Tiger pufferfish	80	3.6	0.31	0.4	22		6		21.3	21.3
Thunnus orientalis	Pacific bluefin tuna	333	4.5	0.15	0.64	37		5		17.1	17.1
Gadus morhua	Atlantic cod	200	4.09	0.14	0.46	19		5		12.1	12.1
Oncorhynchus tshawytscha	Chinook salmon	150	4.4	0.07	0.42	20	2		11.5		11.5
Thunnus maccoyii	Southern bluefin tuna	271.95	3.93	0.14	0.49	21		1		6.8	6.8
Mugil cephalus	Flathead grey mullet	122	2.48	0.23	0.21	20	2	5	2.3	3.8	6.1
Argyrosomus regius	Meagre	230	4.29	0.12	0.5	16		7		5.3	5.3
Thunnus thynnus	Atlantic bluefin tuna	458	4.45	0.08	0.68	75		8		5	5
Lates calcarifer	Barramundi	200	3.83	0.12	0.41	71	6	12	2.1	2	4.1
Hippoglossus hippoglossus	Atlantic halibut	470	4	0.03	0.59	15	1	3	0	2.4	2.4
Acanthopagrus schlegelii	Blackhead seabream	61	3.24	0.14	0.22	14		5		1.5	1.5
Pagrus pagrus	Red porgy	91	3.86	0.13	0.33	23	1	1	0.7	0.5	1.2
Trachurus japonicus	Japanese jack mackerel	50	3.4	0.31	0.35	5		4		1.2	1.2

the trophic web, for example a TL of 2 represents a herbivorous species, while intermediate predators have values around 3.1 and top predators >4.1 (Stergiou et al., 2009).

The risk of genetic impacts was considered only for species native to their farming MEOW. The negative impacts of genetic introgression are positively correlated with escapes frequency (Baskett et al., 2013). Accordingly, a "genetic risk score" was calculated as the product between the number of native species and the $\log_{10}$ transformed mean annual production of native species per MEOW. The pathogenic risk was considered as a proxy for the probability of transmission of disease-causing bacteria, viruses or other microorganisms from farmed fish into wild individuals of the same or different species. Thus, a "pathogenic risk score" was calculated for each MEOW as the number of pathogenic agents, generally pathogen species or genus (Supplementary Table 1), multiplied by the total $\log_{10}$ transformed mean annual production per MEOW. The number of potential pathogenic agents was calculated as the total number of unique pathogen taxa recorded among all fish species farmed in each MEOW. For this purpose, we conducted a comprehensive search of specialised databases, including CABI (www.cabi.org), the Registry of Aquatic Pathology of the Centre for Environment, Fisheries and Aquaculture Science (www.cefas.co.uk/cefas-data-hub/registry-of-aquatic-pathology/), FishBase and FAO aquaculture species factsheets (www.fao.org/fishery/culturedspecies/search/en), as well as literature databases, including ISI Web of Science, Google Scholar and Scopus. The invasive, genetic and diseases risk scores, were scaled between 0 and 100 and summed to provide an overall cumulative risk score. Individual risk scores were mapped at the MEOW scale resulting in global maps of the predicted impact risk associated with escapes of farmed fish. Lastly, we rank provinces nested within realms of the world according to their cumulative risk score.

3. Results

Overall, 75 MEOWs, representing nearly a third (32.3%) of the world's total, supported a total annual production of 3.93 million tonnes (MT) of the thirty most produced fish species in net-pen systems up to 2016 (Fig. 1 and Table 1). There was

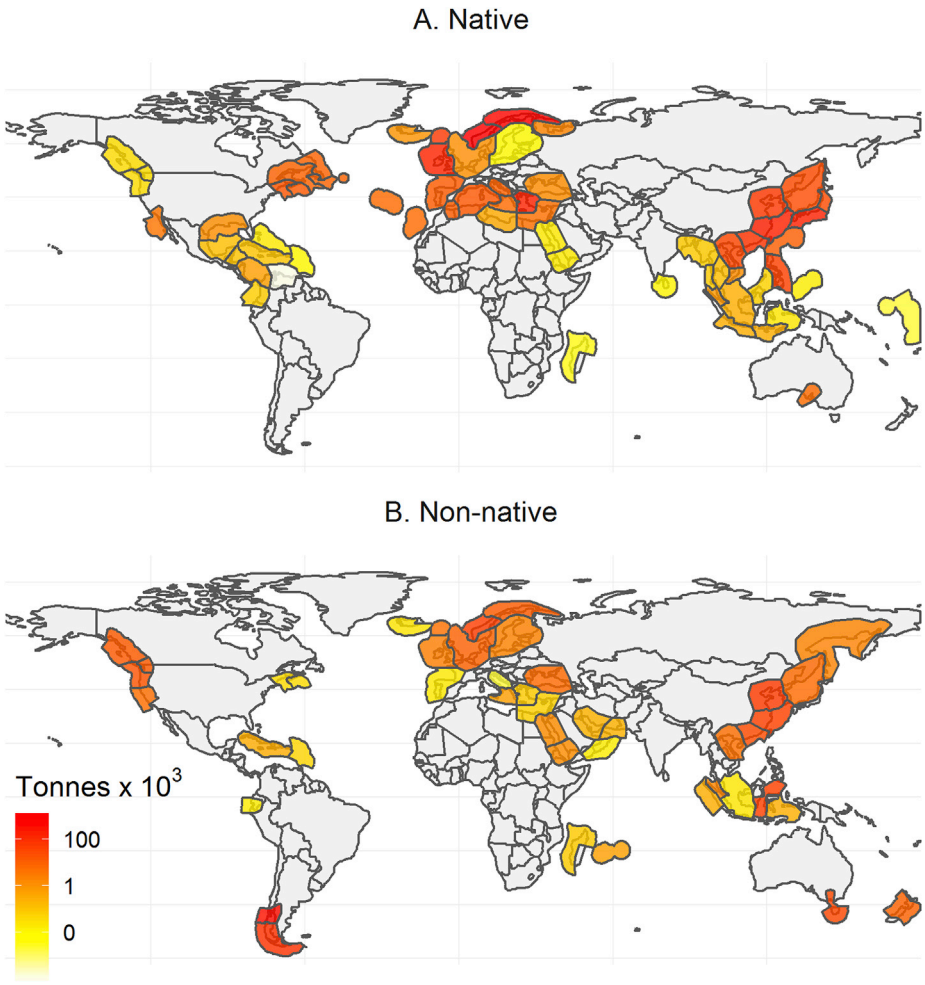

Fig. 1. Mean annual production (tonnes x 10^3) for the thirty most extensively farmed fish species in net-pen systems in Marine Ecoregions of the World by introduction status: native (top panel) and non-native (bottom panel).

large spatial variability in total production, ranging between 0.12 MT in the Southern Caribbean and 0.92 MT per year in Southern Norway (Fig. 1). Out of the total global production, 73.6% (2.90 MT) comprised native fish, whereas 26.4% (1.03 MT) were non-native. Southern Norway MEOW supported the largest production of native fish (0.86 MT, Fig. 1), whereas the highest amount of non-native fish was produced in the Chiloense, in the Magellanic Province of Temperate South America (0.51 MT, Fig. 1). The average number of farmed species per MEOW was 3.17 ± 0.35 SE and it ranged between a minimum of one species, in 27 different MEOWs, and a maximum of 17 species farmed in East China Sea. The highest invasive risk score was predicted for Chiloense (100), in the Magellanic Province; followed by the Yellow Sea (80) and the Channels and Fjords of Southern Chile, also in the Magellanic Province (78, Fig. 2a). The high invasive risk predicted for the two Magellanic MEOWs, was owing to a large production of four non-native salmonid species (0.62 MT), dominated by Atlantic salmon and rainbow trout. These two species ranked 2nd and 5th, respectively, in terms of invasiveness owing to their high trophic level and relatively rapid growth (Table 1). The high invasive score estimated for the Yellow Sea was owing to the large production of three non-native species, namely snubnose pompano, turbot and red drum. High invasive risk was also predicted in MEOWs in other ocean realms, including in the Black Sea (67.9) that supports a large farming industry of non-native rainbow trout; and the Red Sea (56.3), where gilthead seabream, barramundi and European seabass have been introduced and are extensively farmed.

The highest genetic risk score (100) was predicted for East China Sea, followed by the Yellow Sea (81), both in the Temperate Northern Pacific and Southern China, in Central Indo-Pacific (71, Fig. 2b). These MEOWs support a large (0.24, 0.07 and 0.10 MT, respectively) and diverse native fish production (15, 11 and 8 species, respectively), dominated by Japanese seabass, large yellow croaker and snubnose pompano. Additionally, several MEOWs in the Temperate Northern Atlantic scored relatively high in terms of genetic risk, including the Celtic Seas (57), Aegean Sea (57) and South European Atlantic Shelf (56), due to large productions of Atlantic salmon, gilthead seabream and turbot, respectively.

Overall, we identified 462 distinct pathogenic agents associated with the thirty study fish species (Table S1), comprising 61% parasites (Copepoda, Isopoda, Acanthocephala, Cestoda, Trematoda, Clitellata, Monogenea, Nematoda, Myzozoa), 17% of diverse pathogens groups (Amoebozoa, Ciliophora, Apicomplexa, Myzozoa, Microsporidia, Oomycetes and Protozoa), 15% bacteria, 5% viruses and 2% fungi. On average there were 24.8 ± 3.1 SE pathogenic agents recorded per species, with a maximum of 75 for Atlantic bluefin tuna and a minimum of 5 for Japanese jack mackerel (Table 1). At the MEOW level the average number of pathogenic agents was 83 ± 6.7 SE and it fluctuated between 14 in Northern Gulf of Mexico and 227 in East China Sea. The combination of an extensive number of distinct pathogenic agents and a large fish production resulted in the highest disease risk score predicted for East China Sea (100), followed by the Aegean Sea (95) in the Mediterranean, and the South Atlantic Shelf (83) in the Temperate Northern Atlantic (Fig. 2). When summing ecological, genetic and pathogenic risks, highest overall cumulative risk (>125, Fig. 3) was predicted for the Warm and Cold Temperate Northern Pacific (203 and 163, respectively), South China Sea (156) in the Central Indo-Pacific realm, the Temperate Northern Atlantic realm, including the Black Sea (175), Northern European Seas (144), Mediterranean Sea (139) and the Magellanic province (149) in Temperate South America and Red Sea and Gulf of Aden (130) in the Western Indo-Pacific.

4. Discussion

Here we provide the first global quantitative evaluation of risks associated with the impacts of fish escapes from marine net-pen aquaculture systems. Our analysis indicated that a third of marine ecoregions of the world are to some extent at risk from the potential impacts of farmed fish escapes. Aquaculture has been previously considered as an important stressor, mainly due to organic matter inputs, however the combined risks associated with escapes has not been considered at a global scale. We identified risk hotspots for three common stressors associated with escapes of farmed finfish, i.e. the ecological impact of introducing non-native species, impacts of genetic introgression of farmed fish into wild populations and the spread of pathogens and parasites, identifying provinces with high risk for combined impacts of these stressors.

Escapes typically represent average production losses between 1 and 5% (Jackson et al., 2015), either caused by persistent low-level leakage or massive events when millions of fish are released (Soto et al., 2001; Jensen et al., 2010; Sepúlveda et al., 2013). We estimated that 26.5% of the global finfish production comprises non-native species, which equates to a total of 1.74 out of the 6.7 MT annual production of all marine finfish species in 2016 (FAO, 2018). Given the escape rates mentioned above, these production levels translate to a constant introduction of an extremely high biomass and diverse range of potentially invasive non-native fish species into marine ecosystems of the world. Marine invasions are an increasing global phenomenon, adversely affecting a range of ecological and socio-economic values; however, aquaculture managers rarely consider escapes of non-native fish species as a constraint for sensitive habitats. For example, the Magellanic province in Southern Chile was identified as a major hotspot for invasive risk of non-native fish escapes. This province supports the world's largest pen-net production of non-native salmonids (Subsecretaria de Pesca, 2018), farmed in unique and sensitive marine habitats. Here fish escapes are frequent occurrences, both through persistent low-level leakage and massive escape events, estimated at 1 million escapees per year (Sepúlveda et al., 2013). Although Atlantic salmon in Chile is unable to establish wild populations, these escape events have been linked to the establishment of self-sustainable feral populations of rainbow trout and chinook salmon, predation upon native fish, the spread of diseases and pathogens and socio-economical conflicts (Soto et al., 2001). Other provinces with high predicted invasive risk included ecoregions in Cold and Warm Temperate Northwest Pacific. China, the world's largest finfish producer, has introduced >110 fish species into these provinces for aquaculture purposes over the last century (Lin et al., 2015). In addition to constant low-leakage escapes, massive escape events in this province are

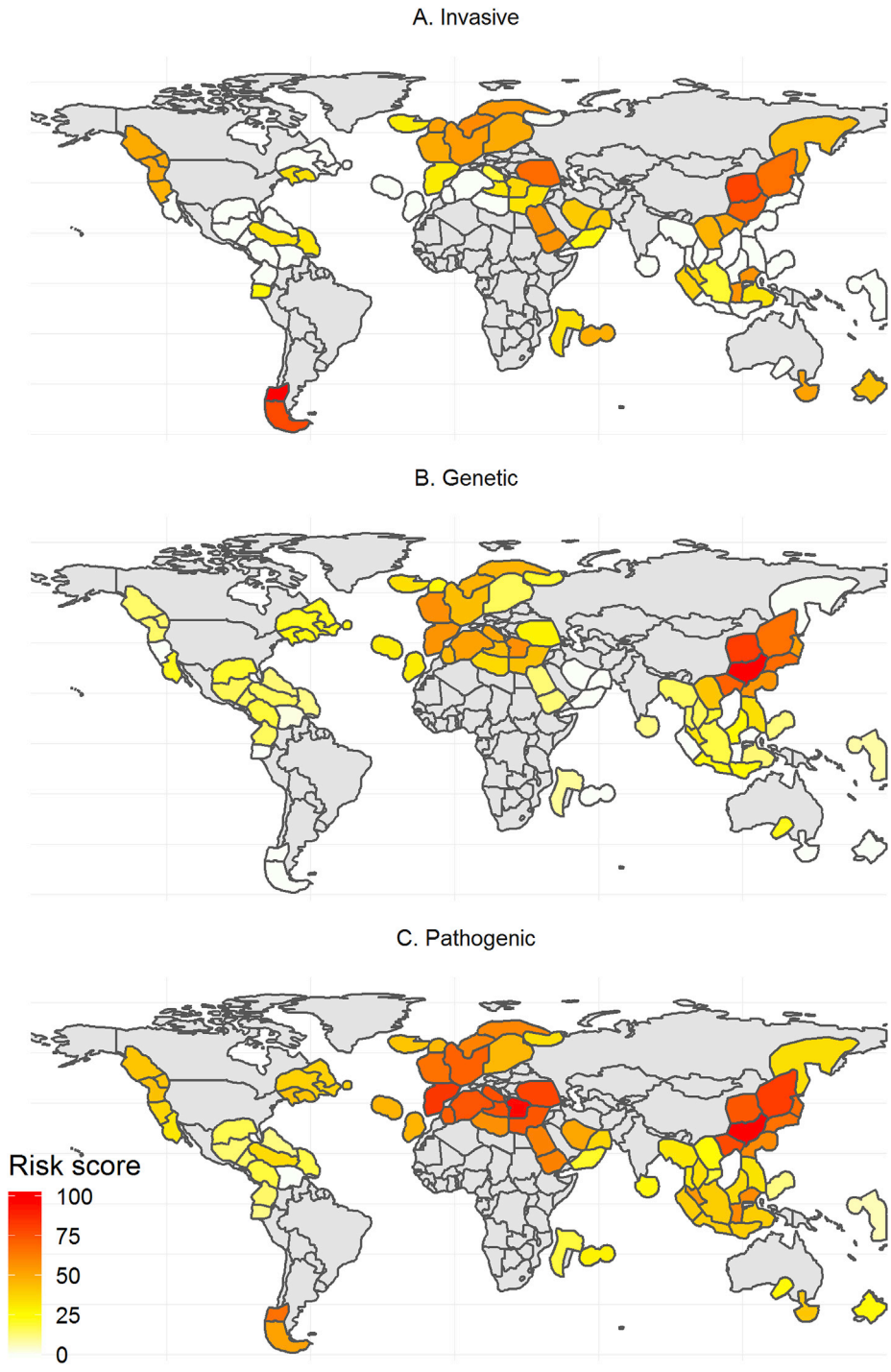

Fig. 2. Global maps of invasive, genetic and pathogenic risk scores associated with the impacts of escapes of the thirsty most extensively farmed marine fish species in net-pen systems in Marine Ecoregions of the World.

frequently caused by floods and storms associated with typhoons (Liao et al., 2010) and their associated ecological impacts are of serious concern (Iseki et al., 2010). For example, red drum, an extensively farmed predatory fish native to the North American Atlantic, has now established feral population in the Warm Temperate Northwest Pacific, where it exerts a strong predatory pressure on a wide range of native prey (Liao et al., 2010). High invasive risk was not only associated with larger producing ecoregions, but also for emergent aquaculture provinces, where several non-native species have been introduced

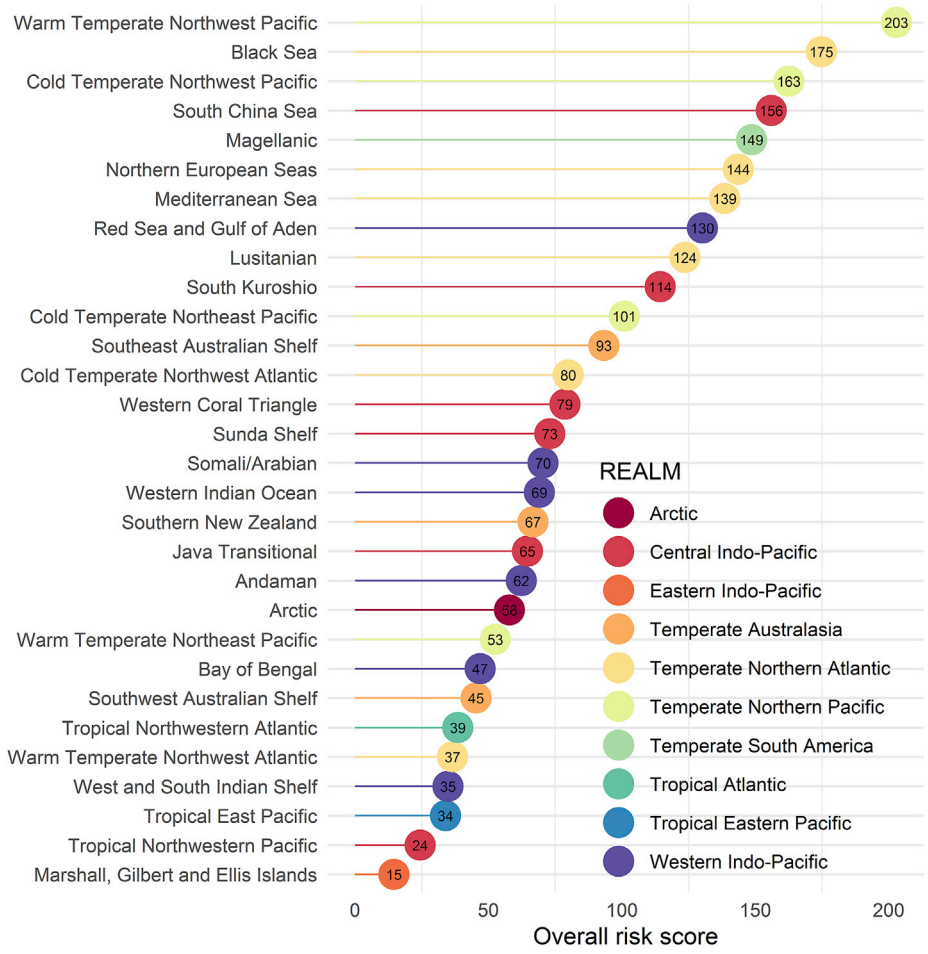

Fig. 3. Cumulative score ranking for each province within reals of the Marine Ecoregions of the World classification based on the sum of invasive, genetic and pathogenic risk scores associated with escapes of the thirsty most extensively farmed marine finfish species in net-pen systems.

for aquaculture purposes, such as, the Red Sea (e.g. gilthead seabream) and the Black Sea (e.g. rainbow trout). Furthermore, these ecoregions are relatively closed systems, where the potential impacts of invasive species are expected to be more pronounced. Therefore, an increase in the perception of this global problem among aquaculture managers and policy-makers is crucial, as the global dependence on non-native species is likely becomes more prevalent in the future, given the industry plans to expand to new farming ecoregions and diversify to new species (Gentry et al., 2017).

However, impacts are not only linked to non-native species, when farmed species are native to their farming ecoregions, a range of interactions are possible, principally through genetic interactions of escaped fish with wild populations. The extent of genetic impacts depends on several factors, including wild stocks' genetic structure and phenotypic variability, the size of the wild populations in relation to the number and frequency of escapes, the degree of escapees' breeding selection and the origin of broodstocks (Arechavala-Lopez et al., 2018). High genetic risk was predicted for provinces that support large and diverse production of native fish, such as Japanese seabass, large yellow croaker and snubnose pompano in Cold and Warm Temperate Northern Pacific and Southern China; and Atlantic salmon, gilthead seabream and turbot in the Northern European Seas, Mediterranean Sea and Lusitanian, respectively. The production of these species is supported by a well-developed hatchery industry (Hong and Zhang, 2003), with a long history of selective breeding. In many cases, this selection is based on a limited number of breeding families that results in considerable genetically distinct individuals compared to their wild counterparts (Gross, 1998). Additionally, wild populations of these farmed species have been depleted or are at dangerous low abundances, thus increasing the risk of genetic impacts and long-term negative effects of introgression. Deleterious genetic interactions have been particularly well documented for Atlantic (McGinnity et al., 2003; Naylor et al., 2005) and chinook salmon (Waples, 1991), including irreversible loss of genetic diversity leading to reduced environmental adaptability, significant fitness reduction and potential local extinction of wild populations. The temperate Northern Pacific and Southern China supports one of the world's largest pen-net finfish industries based on the native large yellow croaker. Wild stocks of this species were virtually depleted by 1980s, before extensive farming based on selective breeding commenced to address food supply and

overfishing (Chen et al., 2018). Farmed croaker escapees have significantly reduced the genetic diversity and environmental adaptability of wild populations (Wang et al., 2012). However, in many cases there is large uncertainty around the genetic risks for less studied species and ecoregions. For example, massive escape events of cobia due to shark attacks are a major problem in the Caribbean, where losses are estimated at 20%, with extreme events up to 90% of the total crop (Benetti et al., 2010). Farmed cobia is genetically different from wild populations; however currently unknown, it is most likely that interbreeding would be detrimental to wild stocks.

Rapid growth of net-pen finfish aquaculture has been also associated with an increase of parasitic and infectious diseases (Kent, 2000) and a concomitant increase in the risk of transmission into wild populations, particularly when farmed and wild fish of the same or closely related species are in close vicinity (Arechavala-Lopez et al., 2013). The risk of spreading pathogens into wild fish and into adjacent farms increases with the movement of escapees; mostly due to their tendency to swing from one farm to another and to interact with wild fish in natural fishing grounds (Arechavala-Lopez et al. 2011, 2012). Escapees can significantly alter the spatio-temporal distribution of pathogens occurring in the wild and in farms. Pathogen spread through escapees depends on the survival and post-escape behaviour of escapees, as well as the pathogen characteristic and levels of fish infection. Identified pathogenic risk hotspots in the Temperate Northern Pacific, including East China Sea and Sea of Japan, and in the Mediterranean, were related to a high diversity and large volume of fish production. As in many other aquaculture ecoregions (e.g. Norway and Chile), fish farms in these ecoregions are plagued with diseases, representing a major challenge for industry (Bondad-Reantaso et al., 2005; Subasinghe et al., 2009). The wide range of pathogens in these ecoregions were dominated by parasitic forms. Parasites with simple life cycles and pelagic life stages, such as monogeneans, trichodinids and sea lice, are the most likely to become a health issue (Heuch et al., 2011). Even though, in many cases the mechanisms for pathogen transmission are unknown and highly unpredictable, there are several examples where escapees served as vectors of transmission of parasites, virus and bacterial diseases, particularly in salmon (Naylor et al., 2005; Krkošek et al., 2007; Johansen et al., 2011). For instance, escapes of farmed salmonids have been linked to outbreaks of parasitic sea lice in several farming regions (Naylor et al., 2005; Costello 2006, 2009; Krkošek et al., 2007). In the Mediterranean, farmed and wild species shared a wide range of pathogens, however there is ambiguous evidence for pathogen transmission (Fernandez-Jover et al., 2010). In any cases, provided evidence or as a precautionary principle, the pathogenic risk related to fish escapees should be taken in consideration in epidemiological approaches for fish health management.

When considering the cumulative risks for invasive, genetic and pathogenic impact, the warm temperate Northwest Pacific and the Black Sea ranked highest. Although there is a good understanding of the impacts of individual stressors, there has been much less research conducted on the effects of multiple stressors acting simultaneously. These ecosystems are already subjected to a wide range of stressors including habitat degradation, overfishing, pollution, invasive species, ocean acidification and climate change, among many others (Halpern et al., 2008). For a practical and realistic perspective, knowledge-based risk management and effective mitigation measures for the cumulative impacts of fish escapes (Dempster et al., 2018), is the way forward for the sustainable development of aquaculture. Some important avenues to be followed, among others, to minimise and eventually avert the risks are: (i) for prevention, develop suitable technologies to avoid escapes as much as possible (e.g. Jensen et al., 2010), increase the training of worker and aquaculture managers, as well as considering the risk of escapes during the site selection process; (ii) for mitigation, improve management measures to increase escapees' recapture success (Izquierdo-Gomez and Sanchez-Jerez, 2016), (iii) intensify biotechnological research aiming at reducing reproductive capability of farmed fish (e.g. triploids Benfey, 2001), reducing the possibility of cross reproduction. Additionally, the translocation of fish species to other ecoregions outside of their native distributional ranges must be considering as a high-risk activity because of the negative ecological and socio-economic consequences.

Elucidating the simultaneous risks associated to multiple farmed species is one of the major challenges for the aquaculture industry and needs to be addressed urgently to underpin management measures to halt the impacts to the functioning and structure of marine ecosystems. Innovative approaches to fish farming, as well as a better understanding of the potential cumulative impacts of large-scale ocean farming, could help marine aquaculture to become more environmentally sustainable. This study provides global insights into the extent and magnitude risks associated with fish escapes, showing that nearly a third of marine ecoregions of the world are vulnerable to their potential impacts. We showed that over a quarter of the global farmed fish production comprise non-native species, posing a pressing and widespread risk for the impacts of ecological invasions. Furthermore, wild fish populations in hotspot regions supporting a large and diverse production of native fish are at high genetic and pathogenic risk. Sound operational practices coupled with effective management and mitigation measures to reduce fish escapes need to be considered if ecosystems impacts are to be avoided, particularly in identified hotspots, and the sustainable development of the aquaculture industry promoted.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

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References

Arechavala-Lopez, P., Uglem, I., Fernandez-Jover, D., Bayle-Sempere, J., Sanchez-Jerez, P., 2011. Immediate post-escape behaviour of farmed seabass (*Dicentrarchus labrax* L.) in the Mediterranean Sea. J. Appl. Ichthyol. 27, 1375–1378.

Arechavala-Lopez, P., Uglem, I., Fernandez-Jover, D., Bayle-Sempere, J.T., Sanchez-Jerez, P., 2012. Post-escape dispersion of farmed seabream (*Sparus aurata* L.) and recaptures by local fisheries in the Western Mediterranean Sea. Fish. Res. 121, 126–135.

Arechavala-Lopez, P., Sanchez-Jerez, P., Bayle-Sempere, J.T., Uglem, I., Mladineo, I., 2013. Reared fish, farmed escapees and wild fish stocks—a triangle of pathogen transmission of concern to Mediterranean aquaculture management. Aquacult. Environ. Interact. 3, 153–161.

Arechavala-Lopez, P., Toledo-Guedes, K., Izquierdo-Gomez, D., Šegvić-Bubić, T., Sanchez-Jerez, P., 2018. Implications of sea bream and sea bass escapes for sustainable aquaculture management: a review of interactions, risks and consequences. Rev. Fish. Sci. Aquacult. 26, 214–234.

Arismendi, I., Soto, D., Penaluna, B., Jara, C., Leal, C., León-Muñoz, J., 2009. Aquaculture, non-native salmonid invasions and associated declines of native fishes in Northern Patagonian lakes. Freshw. Biol. 54, 1135–1147.

Baskett, M.L., Burgess, S.C., Waples, R.S., 2013. Assessing strategies to minimize unintended fitness consequences of aquaculture on wild populations. Evol. Appl. 6, 1090–1108.

Benetti, D.D., O'Hanlon, B., Rivera, J.A., Welch, A.W., Maxey, C., Orhun, M.R., 2010. Growth rates of cobia (*Rachycentron canadum*) cultured in open ocean submerged cages in the Caribbean. Aquaculture 302, 195–201.

Benfey, T.J., 2001. Use of sterile triploid Atlantic salmon (*Salmo salar* L.) for aquaculture in New Brunswick, Canada. ICES J. Mar. Sci. 58, 525–529.

Bolstad, G.H., Hindar, K., Robertsen, G., Jonsson, B., Sægrov, H., Diserud, O.H., Fiske, P., Jensen, A.J., Urdal, K., Næsje, T.F., Barlaup, B.T., Florø-Larsen, B., Lo, H., Niemelä, E., Karlsson, S., 2017. Gene flow from domesticated escapes alters the life history of wild Atlantic salmon. Nat. Ecol. Evol. 1, 0124.

Bondad-Reantaso, M.G., Subasinghe, R.P., Arthur, J.R., Ogawa, K., Chinabut, S., Adlard, R., Tan, Z., Shariff, MJVp, 2005. Disease and health management in Asian aquaculture, 132, 249–272.

Chen, S., Su, Y., Hong, W., 2018. Aquaculture of the large yellow croaker. In: Gui, J., Tang, Q., Li, Z., Liu, J., De Silva, S. (Eds.), Aquaculture in China: Success Stories and Modern Trends. John Wiley & Sons, Oxford.

Costello, M.J., 2006. Ecology of sea lice parasitic on farmed and wild fish. Trends Parasitol. 22, 475–483.

Costello, M.J., 2009. How sea lice from salmon farms may cause wild salmonid declines in Europe and North America and be a threat to fishes elsewhere. Proc. R. Soc. Biol. Sci. 276, 3385–3394.

Crawford, S.S., Muir, A.M., 2008. Global introductions of salmon and trout in the genus *Oncorhynchus*: 1870–2007. Rev. Fish Biol. Fish. 18, 313–344.

Crowl, T.A., Townsend, C.R., McIntosh, A.R., 1992. The impact of introduced brown and rainbow trout on native fish: the case of Australasia. Rev. Fish Biol. Fish. 2, 217–241.

Dempster, T., Uglem, I., Sanchez-Jerez, P., Fernandez-Jover, D., Bayle-Sempere, J., Nilsen, R., Bjørn, P.A., 2009. Coastal salmon farms attract large and persistent aggregations of wild fish: an ecosystem effect. Mar. Ecol. Prog. Ser. 385, 1–14.

Dempster, T., Arechavala-Lopez, P., Barrett, L.T., Fleming, I.A., Sanchez-Jerez, P., Uglem, I., 2018. Recapturing escaped fish from marine aquaculture is largely unsuccessful: alternatives to reduce the number of escapees in the wild. Rev. Aquac. 10, 153–167.

Diamant, A., Colorni, A., Ucko, M., 2007. Parasite and disease transfer between cultured and wild coastal marine fish. CIESM Workshop Monogr. 32, 49–54.

FAO, 2018. The State of World Fisheries and Aquaculture 2018 - Meeting the Sustainable Development Goals. Rome. http://www.fao.org/3/i9540en/I9540EN.pdf.

Fernandez-Jover, D., Faliex, E., Sanchez-Jerez, P., Sasal, P., Bayle-Sempere, J.T., 2010. Coastal fish farming does not affect the total parasite communities of wild fish in SW Mediterranean. Aquaculture 300, 10–16.

Froese, R., Pauly, D., 2000. FishBase 2000: concepts, Design and Data Sources. International Centre for Living Aquatic Resources Management url. www.fishbase.org.

Gentry, R.R., Froehlich, H.E., Grimm, D., Kareiva, P., Parke, M., Rust, M., Gaines, S.D., Halpern, B.S., 2017. Mapping the global potential for marine aquaculture. Nat. Ecol. Evol. 1, 1317.

Glover, K.A., Dahle, G., Westgaard, J.I., Johansen, T., Knutsen, H., Jørstad, K.E., 2010. Genetic diversity within and among Atlantic cod (*Gadus morhua*) farmed in marine cages: a proof-of-concept study for the identification of escapees. Anim. Genet. 41, 515–522.

Gomez-Uchida, D., Sepulveda, M., Ernst, B., Contador, T.A., Neira, S., Harrod, C., 2018. Chile's salmon escape demands action. Science 361, 857.

Gross, M.R., 1998. One species with two biologies: Atlantic salmon (*Salmo salar*) in the wild and in aquaculture. Can. J. Fish. Aquat. Sci. 55, 131–144.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H. S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., 2008. A global map of human impact on marine ecosystems. Science 319, 948–952.

Heuch, P.A., Jansen, P.A., Hansen, H., Sterud, E., MacKenzie, K., Haugen, P., Hemmingsen, W., 2011. Parasite faunas of farmed cod and adjacent wild cod populations in Norway: a comparison. Aquacult. Environ. Interact. 2, 1–13.

Hong, W., Zhang, Q., 2003. Review of captive bred species and fry production of marine fish in China. Aquaculture 227, 305–318.

Iseki, T., Mizuno, K., Ohta, T., Nakayama, K., Tanaka, M., 2010. Current status and ecological characteristics of the Chinese temperate bass *Lateolabrax* sp., an alien species in the western coastal waters of Japan. Ichthyol. Res. 57, 245–253.

Izquierdo-Gomez, D., Sanchez-Jerez, P., 2016. Management of fish escapes from Mediterranean Sea cage aquaculture through artisanal fisheries. Ocean Coast Manag. 122, 57–63.

Jackson, D., Drumm, A., McEvoy, S., Jensen, Ø., Mendiola, D., Gabiña, G., Borg, J.A., Papageorgiou, N., Karakassis, Y., Black, K.D., 2015. A pan-European valuation of the extent, causes and cost of escape events from sea cage fish farming. Aquaculture 436, 21–26.

Jensen, Ø., Dempster, T., Thorstad, E., Uglem, I., Fredheim, A., 2010. Escapes of fishes from Norwegian sea-cage aquaculture: causes, consequences and prevention. Aquacult. Environ. Interact. 1, 71–83.

Johansen, L.-H., Jensen, I., Mikkelsen, H., Bjørn, P.-A., Jansen, P., Bergh, Ø., 2011. Disease interaction and pathogens exchange between wild and farmed fish populations with special reference to Norway. Aquaculture 315, 167–186.

Kaschner, K., Kesner-Reyes, K., Garilao, C., Rius-Barile, J., Rees, J., Froese, R., 2006. AquaMaps: Predicted Range Maps for Aquatic Species. World wide web electronic publication. Version 10/2019. www.aquamaps.org.

Kent, M.L., 2000. Marine netpen farming leads to infections with some unusual parasites. Int. J. Parasitol. 30, 321–326.

Kolar, C.S., Lodge, D.M., 2001. Progress in invasion biology: predicting invaders. Trends Ecol. Evol. 16, 199–204.

Krkošek, M., Ford, J.S., Morton, A., Lele, S., Myers, R.A., Lewis, M.A., 2007. Declining wild salmon populations in relation to parasites from farm salmon. Science 318, 1772–1775.

Liao, Y.C., Chen, L.S., Shao, K.T., 2010. The predatory Atlantic red drum, *Sciaenops ocellatus*, has invaded the western Taiwanese coast in the Indo-West Pacific. Biol. Invasions 12, 1961–1965.

Lin, Y., Gao, Z., Zhan, A., 2015. Introduction and use of non-native species for aquaculture in China: status, risks and management solutions. Rev. Aquac. 7, 28–58.
McGinnity, P., Prodöhl, P., Ferguson, A., Hynes, R., Maoiléidigh, Nó, Baker, N., Cotter, D., O'Hea, B., Cooke, D., Rogan, G., 2003. Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon. Proc. R. Soc. Lond. Ser. B Biol. Sci. 270, 2443–2450.
Miralles, L., Mrugala, A., Sanchez-Jerez, P., Juanes, F., Garcia-Vazquez, E., 2016. Potential impact of Mediterranean aquaculture on the wild predatory bluefish. Mar. Coast. Fish. 8, 92–99.
Murray, A.G., 2009. Using simple models to review the application and implications of different approaches used to simulate transmission of pathogens among aquatic animals. Prev. Vet. Med. 88, 167–177.
Naylor, R., Hindar, K., Fleming, I.A., Goldburg, R., Williams, S., Volpe, J., Whoriskey, F., Eagle, J., Kelso, D., Mangel, M., 2005. Fugitive salmon: assessing the risks of escaped fish from net-pen aquaculture. Bioscience 55, 427–437.
Olivier, G., 2002. Disease interactions between wild and cultured fish-Perspectives from the American Northeast (Atlantic Provinces). Bull. Eur. Assoc. Fish Pathol. 22, 102–109.
Pauly, D., Zeller, D., 2015. Sea Around Us Concepts, Design and Data. seaaroundus.org.
Pearson, T., Black, K., 2000. The environmental impacts of marine fish cage culture. In: Environmental Impacts of Aquaculture, pp. 1–31.
Sala, E., Kizilkaya, Z., Yildirim, D., Ballesteros, E., 2011. Alien marine fishes deplete algal biomass in the eastern Mediterranean. PLoS One 6, e17356.
Sanchez-Jerez, P., Fernandez-Jover, D., Bayle-Sempere, J., Valle, C., Dempster, T., Tuya, F., Juanes, F., 2008. Interactions between bluefish *Pomatomus saltatrix* (L.) and coastal sea-cage farms in the Mediterranean Sea. Aquaculture 282, 61–67.
Sarà, G., 2007. A meta-analysis on the ecological effects of aquaculture on the water column: dissolved nutrients. Mar. Environ. Res. 63, 390–408.
Sepúlveda, M., Arismendi, I., Soto, D., Jara, F., Farias, F., 2013. Escaped farmed salmon and trout in Chile: incidence, impacts, and the need for an ecosystem view. Aquacult. Environ. Interact. 4, 273–283.
Shea, K., Chesson, P., 2002. Community ecology theory as a framework for biological invasions. Trends Ecol. Evol. 17, 170–176.
Simberloff, D., 2009. The role of propagule pressure in biological invasions. Annu. Rev. Ecol. Evol. Systemat. 40, 81–102.
Soto, D., Jara, F., Moreno, C., 2001. Escaped salmon in the inner seas, southern Chile: facing ecological and social conflicts. Ecol. Appl. 11, 1750–1762.
Soto, D., Aguilar-Manjarrez, J., Brugère, C., Angel, D., Bailey, C., Black, K., Edwards, P., Costa-Pierce, B., Chopin, T., Deudero, S., 2008. Applying an ecosystem-based approach to aquaculture: principles, scales and some management measures. Build. Ecosyst. Approach Aquacult. (14).
Spalding, M.D., Fox, H.E., Allen, G.R., Davidson, N., Ferdaña, Z.A., Finlayson, M., Halpern, B.S., Jorge, M.A., Lombana, A., Lourie, S.A.J.A.B., 2007. Marine Ecoregions of the World: a Bioregionalization of Coastal and Shelf Areas, vol. 57, pp. 573–583.
Stergiou, K.I., Tsikliras, A.C., Pauly, D., 2009. Farming up Mediterranean food webs. Conserv. Biol. 23, 230–232.
Subasinghe, R., Soto, D., Jia, J., 2009. Global aquaculture and its role in sustainable development. Rev. Aquac. 1, 2–9.
Subsecretaria de Pesca, 2018. Informe sectorial de pesca y acuicultura. Informe sectorial de pesca y acuicultura. http://www.subpesca.cl/portal/618/articles-103127_documento.pdf.
Thorstad, E.B., Økland, F., Aarestrup, K., Heggberget, T.G., 2008. Factors affecting the within-river spawning migration of Atlantic salmon, with emphasis on human impacts. Rev. Fish Biol. Fish. 18, 345–371.
Toledo-Guedes, K., Sanchez-Jerez, P., Brito, A., 2014a. Influence of a massive aquaculture escape event on artisanal fisheries. Fish. Manag. Ecol. 21, 113–121.
Toledo-Guedes, K., Sanchez-Jerez, P., Benjumea, M.E., Brito, A., 2014b. Farming-up coastal fish assemblages through a massive aquaculture escape event. Mar. Environ. Res. 98, 86–95.
Valero-Rodriguez, J.M., Toledo-Guedes, K., Arechavala-Lopez, P., Izquierdo-Gomez, D., Sanchez-Jerez, P., 2015. The use of trophic resources by *Argyrosomus regius* (Asso, 1801) escaped from Mediterranean offshore fish farms. J. Appl. Ichthyol. 31, 10–15.
Vila-Gispert, Anna, Alcaraz, Carles, García-Berthou, Emili, 2005. Life-history traits of invasive fish in small Mediterranean streams. Biological Invasions 7 (1), 107.
Wang, L., Shi, X., Su, Y., Meng, Z., Lin, H., 2012. Loss of genetic diversity in the cultured stocks of the Large Yellow Croaker, *Larimichthys crocea*, revealed by microsatellites. Int. J. Mol. Sci. 13, 5584–5597.
Waples, R.S., 1991. Genetic interactions between hatchery and wild salmonids: lessons from the Pacific Northwest. Can. J. Fish. Aquat. Sci. 48, 124–133.